



ARL-CR-0781 • SEP 2015



A Process for the Development of Rapid Prototype Light Pipes

prepared by Barry J Kline

*TKC Global Solutions LLC, Suite 400 North
13873 Park Center Road, Herndon, VA*

under contract W911QX-14-C-0016

Approved for public release; distribution is unlimited.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.



A Process for the Development of Rapid Prototype Light Pipes

prepared by Barry J Kline
TKC Global Solutions LLC, Suite 400 North
13873 Park Center Road, Herndon, VA

under contract W911QX-14-C-0016

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) September 2015		2. REPORT TYPE Contractor		3. DATES COVERED (From - To) 1-30 June 2015	
4. TITLE AND SUBTITLE A Process for the Development of Rapid Prototype Light Pipes				5a. CONTRACT NUMBER W911QX-14-C-0016	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Barry J Kline				5d. PROJECT NUMBER 350.14100.000.001	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) TKC Global Suite 400 North 13873 Park Center Rd Herndon, VA 20171				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-WML-F Aberdeen Proving Ground, MD 5066				10. SPONSOR/MONITOR'S ACRONYM(S) ARL	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) ARL-CR-0781	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Researchers at the US Army Research Laboratory's Guidance Technology Branch have demonstrated the ability to rapidly fabricate uniquely configured optical light pipes using stereolithography and postprocessing with an airbrush. This technique represents an improved option for transmitting optical status indicators from electronics inside a smart projectile to a location on the exterior of the projectile body.					
15. SUBJECT TERMS light pipe, rapid prototype, 3-D systems viper, objet connex 500					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON Barry Kline
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 410-306-1203

Contents

List of Figures	iv
Preface	v
1. Background	1
2. Technical Approach	4
3. Results	7
4. Future Work	8
5. References	9
Appendix. Light Pipe Schematic	11
List of Symbols, Abbreviations, and Acronyms	13
Distribution List	14

List of Figures

Fig. 1	Laser TIR in poly(methyl methacrylate).....	2
Fig. 2	Snell's law = ($n_i * \sin f_i = n_r * \sin f_r$).....	3
Fig. 3	CAD model of 5-LED light pipe array	4
Fig. 4	Light pipe 3-D printed using WaterSheed XC 11122 resin.....	5
Fig. 5	Light pipe 3-D printed using Veroclear (note cloudy surface).....	6
Fig. 6	Light pipe after airbrushing	7
Fig. 7	Light pipe in action	7

Preface

The research reported in this document was performed in connection with contract/instrument W911QX-14-C-0016 with the US Army Research Laboratory. The views and conclusions contained in this document are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the US Army Research Laboratory or the US Government unless so designated by other authorized documents. Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. The US Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

INTENTIONALLY LEFT BLANK.

1. Background

The mission of the US Army Research Laboratory's (ARL's) Guidance Technology Branch (GTB) includes development and implementation of diagnostic electronics and guidance systems for smart projectiles. These systems are typically installed within a confined internal volume of a projectile and are g-hardened to survive the acceleration loads associated with gun launch. The electronic components of these systems often require externally visible status indicators so that test personnel can efficiently determine the current operating status of the system. Example status messages include power on/off, GPS receiver power, onboard data recorder status, battery health, etc. Previously developed systems used light-emitting diodes (LEDs) installed into a hole drilled in the external shell of the projectile body and connected to internal electronics by wires. This method limits the number of messages that can be displayed for a given form factor and results in components that are cumbersome to fabricate and install.

Light pipes, a subset of fiber optics, are capable of transmitting visible light emitted by an LED from the mounting location of the LED on a printed circuit board (PCB) to the exterior of a housing. Light pipes allow the use of robust PCB-mounted LEDs even if the entire circuit board is enclosed. This configuration is particularly advantageous for electronics systems developed by GTB because smart munitions typically require that electronic components be housed within an internal volume located along the centerline of the projectile relatively far from where indicators need to be viewed.

There are 2 primary styles of light pipes, those that consist of a mirrored tube and those that utilize the optical phenomenon of total internal reflection (TIR). Most light pipes used commercially are of the TIR variety. The TIR phenomenon is a complete reflection of a ray of light passing through an incidence medium such as water or glass by the surrounding surfaces back into the medium (Fig. 1).¹ TIR effectively traps the light within the medium it is traveling through until it strikes a surface with the correct geometry to allow the light to escape. In contrast, the mirrored tube light pipe style uses a reflective outer coating to contain the light within the pipe.

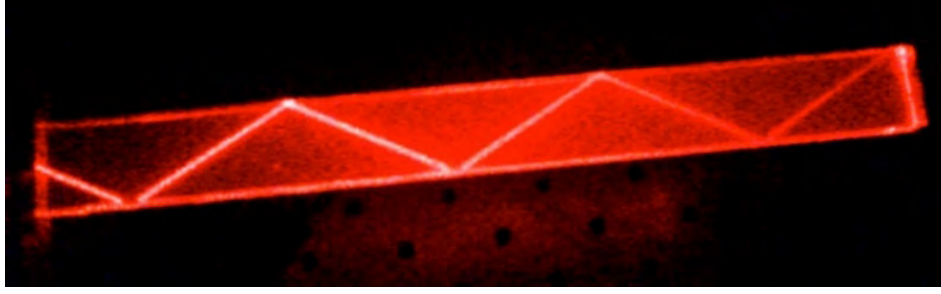


Fig. 1 Laser TIR in poly(methyl methacrylate)²

The theoretical performance of TIR light pipes with respect to light transmission efficiency can be scientifically analyzed using Snell's law and the principle of Fresnel loss.¹ Snell's law describes the governing relationship of optical interactions occurring at the interface between 2 optical mediums. This law is defined by the equation

$$(n_i * \sin f_i = n_r * \sin f_f). \quad (1)$$

Snell's law relates the angle of refraction f_f of a light ray approaching an interface at incidence angle f_i , to the index of refraction properties n_i and n_r of the 2 mediums as depicted in Fig. 2. Solving Snell's law for a refraction angle equal to 90° identifies the critical incidence angle required to create the TIR phenomenon. Angles of incidence greater than this critical angle will create light that becomes trapped inside the initial medium, TIR. It is apparent from Fig. 2 that if the angle of refraction f_f is increased beyond 90° , the light ray will remain within the incidence medium resulting in TIR of the transmitted light.

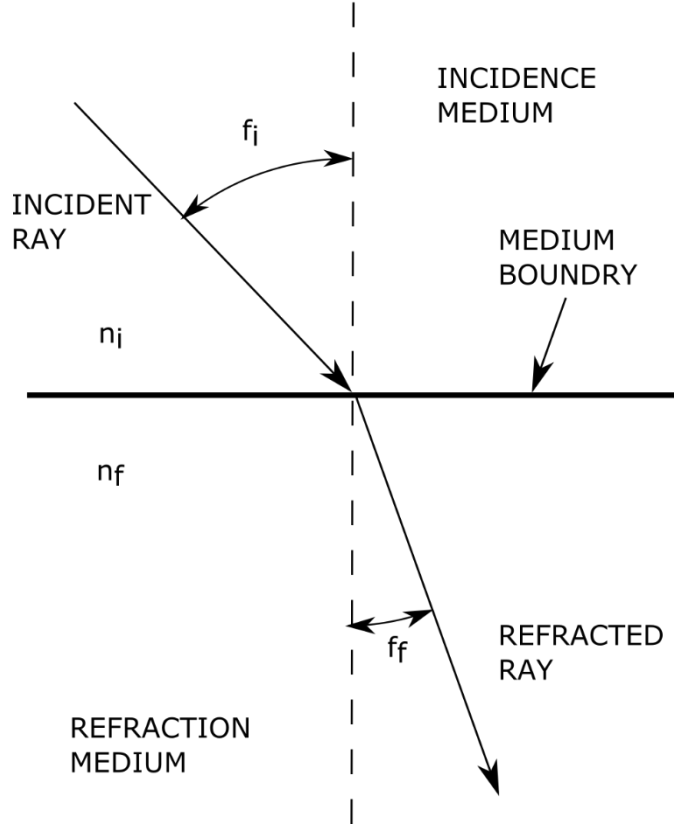


Fig. 2 Snell's law = $(n_i * \sin f_i = n_r * \sin f_f)^1$

Fresnel loss quantifies (percent) the optical intensity loss at an interface between 2 dissimilar mediums, such as glass and air. The equation for calculation Fresnel loss is

$$100 * \left[\frac{n_i - n_f}{n_i + n_f} \right]^2, \quad (2)$$

where the variables are the same as those previously used to explore Snell's law. The main design implication of Fresnel loss is that any time a ray of light goes from one medium to the next, there is a loss of intensity. Reducing the total number of instances in which a light ray passes between mediums generally improves the total transition performance of an optical system.

The mirrored light pipe or light tube³ is a less common style of light pipe but has advantages over the TIR style for some applications. A mirrored light pipe consists of a clear polymer, glass, or air medium for the light to travel through, surrounded by a reflective surface that contains the light inside the pipe. This form of light pipe has lower transition efficiency than TIR light due to scattering of light rays inside the pipe as they reflect off the outer surfaces. However, mirrored light pipes are significantly simpler to manufacture because light transmission can be

achieved without having to meet the optical constraints for TIR as specified by Snell's Law. Devices of this type are often used to transmit sunlight to the inside of buildings that do not have direct access to exterior windows.

Commercial-off-the-shelf (COTS) light pipes of both types are available in limited geometric configurations and for a limited subset of LED packages. Because of the custom nature of precision munitions developed by GTB as well as the limitations in physical space geometry, the available COTS components are inadequate. To fill this gap, GTB has developed a process for creating custom-designed light pipes.

2. Technical Approach

ARL chose to pursue the design of a mirrored light pipe commonly known as a light tube. The main reason for this choice is that TIR light pipes must be surrounded by an optical medium of lower index of refraction than the incidence material of the light pipe, such as air surrounding glass. In general, smart projectile electronics enclosures are filled with potting material to support the components for g-hardening to ensure survivability of the electronics during gun launch. This potting process removes all of the air within the electronics enclosure and precludes the TIR phenomenon required for a light pipe of that style to function.

The light pipe prototyped by GTB was designed using computer-assisted design (CAD) to model of a component designed to fit directly over a PCB-mounted LED array (Fig. 3). A schematic drawing of the light pipe is shown in the Appendix. The modeled component consists of cavities to tightly enclose the board-mounted LEDs and rods to transmit the emitted light to the external display panel. The material thickness between the top of the cavities and the bottom of the transmission rods was minimized to reduce cross talk between the different LEDs.

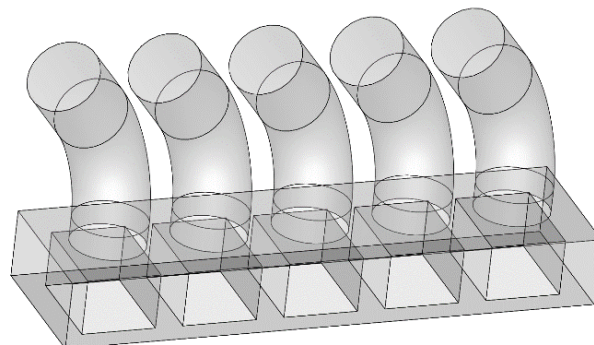


Fig. 3 CAD model of 5-LED light pipe array

The data sheets for several material options were evaluated based on optical clarity. Two candidate materials were specified by the manufacturer to be extremely clear and thus suitable for light pipe fabrication. The first production option was Somos WaterSheed XC 11122 resin,⁴ with an index of refraction of 1.514, printed using a 3D Systems Viper SLA machine.⁵ The second option was Veroclear resin⁶ synthesized using an Objet Connex 500⁷ machine. An exact index of refraction value for Veroclear is not given on the data sheet; however, literature on the manufacturer's website suggests that the material is clear enough to produce lenses for eye glasses. The light pipe CAD model was 3-dimensionally (3-D) printed out of these 2 different materials to determine the best material choice for the light pipe in a practical application. Evaluation of the prototypes resulted in the selection of components printed using Somos WaterSheed XC 11122 resin as the best available option (Fig. 4). This combination outperformed parts produced using the Veroclear resin in terms of optical clarity and surface finish (Fig. 5). The main performance disadvantage of the Veroclear parts is that the parts produced by the Objet machine have a waxy outer layer that scatters light entering the part and creates an adhesion problem during application of a reflective outer finish.



Fig. 4 Light pipe 3-D printed using WaterSheed XC 11122 resin



Fig. 5 Light pipe 3-D printed using Veroclear (note cloudy surface)

Once the component has been 3-D printed, an opaque finish needs to be applied to the exterior of the plastic part to reflect transmitted light and contain it within the optic. An experiment was conducted with different reflective coatings to evaluate the light transmission, the observed cross talk, and opacity.

Kapton tape masking was applied to the cavities where the LEDs are to be placed and to the rod tips where the light is to be viewed. Initially, aerosol-emitted spray paints in both white and black were evaluated as finish options. Black paint performed poorly due to large proportions of the emitted light being absorbed by the paint. The white paint provided significantly better light transmission. However, aerosol-emitted paint lacked the precision to fully cover the intricate geometry of the component and created areas of uneven paint thickness. This inconsistent coating led to portions of the light escaping out the sides of the light pipe where paint thickness was lacking, and resulted in inadequate overall transition efficiency.

Application of opaque white paint to the light pipe using an airbrush provided an improved surface finish. An Iwata Kustom TH airbrush⁸ and Wicked Colors Wicked Opaque White⁹ paint were selected. The adjustability of this applicator allowed for precise and even application of paint to the details of the part. Several thin layers of paint were applied to ensure full coverage without generating areas of excessive paint thickness (Fig. 6). Full coverage of all intricate surface features of the device led to greatly improved transition efficiency.

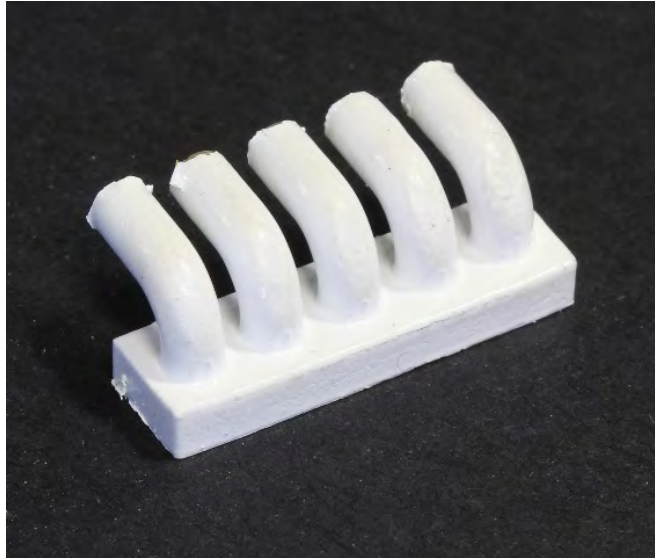


Fig. 6 Light pipe after airbrushing

3. Results

The finished product was overlaid on an appropriately sized surface-mounted LED, an OSRAM blue surface-mounted diode LED,¹⁰ for testing (Fig. 7). The level of light transmission through the intended rod is adequate for observation in bright lighting conditions, and it is clear which indicator is illuminated. Some cross talk between rods is observed and some light leaks through the opaque coating, but this loss of emitted light will not affect the functionality of the light pipe for its intended use.

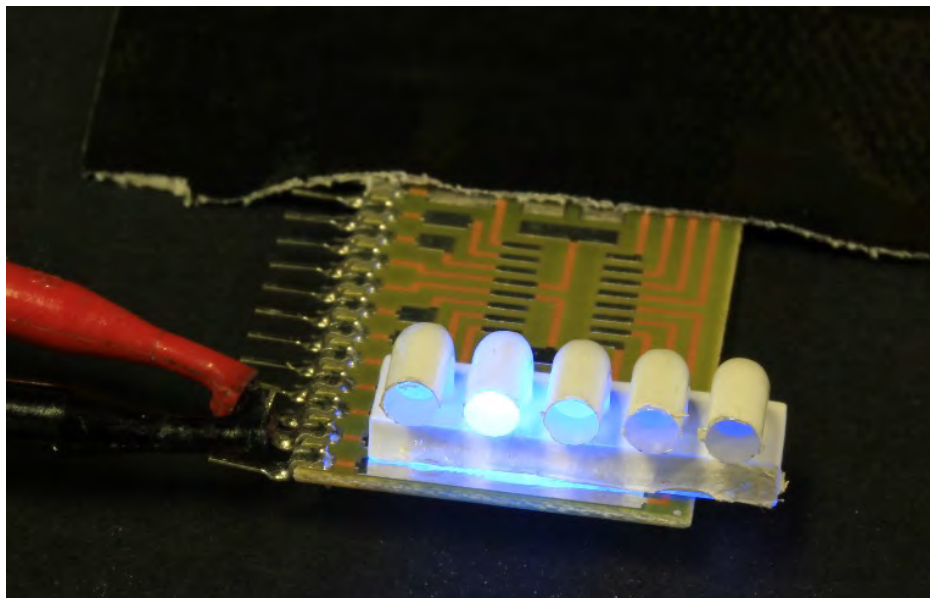


Fig. 7 Light pipe in action

4. Future Work

Additional light pipe configurations are being researched, such as curricular arrays and more tortuous passages. Optical efficiency and sources of transition loss have not been explicitly evaluated and may lead to design improvements. Higher performance paint capable of increased reflection to contain the light inside the pipe may improve the brightness of the observed indicator light.

5. References

1. Light guide techniques for LEDs [accessed 2015 June 25]. www.avagotech.com/docs/5988-7057EN.
2. Poly(methyl methacrylate) [accessed 2015 June 25]. <http://www.polymerprocessing.com/polymers/PMMA.html>.
3. Light pipes or tubes [accessed 2015 June 25]. <http://www.slideshare.net/rizwanbasharat3/light-pipes-or-tubes>.
4. Somos WaterShed XC 11122 resin [accessed 2015 June]. http://www.dsm.com/products/somos/en_US/offerings/offerings-somos-water-shed.html.
5. 3D Systems Viper SLA Machine [accessed 2015 June 25]. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDYQFjAA&url=http%3A%2F%2Fwww.3dsystems.com%2Fproducts%2Fdatafiles%2Fviper%2Fdatasheets%2FInternational%2Fviper_si2_uk.qxd.pdf&ei=8TCEVZHEDIOZgwSlj6D4Cg&usq=AFQjCNGao_UD6caPzjndY7B3Aj8DQ9f-Lw&sig2=XJYFgTZKcZTLjnbN1tnrA&bvm=bv.96042044,d.eXY.
6. Objet Veroclear [accessed 2015 June 25]. <http://www.stratasys.com/materials/polyjet/transparent>.
7. Objet Connex 500 [accessed 2015 June 25]. <http://www.stratasys.com/3d-printers/design-series/connex-systems>.
8. Iwata Kustom TH Airbrush [accessed 2015 June]. <http://www.iwata-medeia.com/products/iwata-airbrushes/kustom-series/kustom-th/>.
9. Wicked colors, wicked opaque white [accessed 2015 June]. <http://www.createxcolors.com/products/wickedcolors/wickeddetail.html#prettyPhot>.
10. OSRAM Blue SMD LED – Mouser - LB T673-L2P1-25-Z [accessed 2015 June 25]. <http://www.mouser.com/ProductDetail/Osram-Opto-Semiconductor/LB-T673-L2P1-25-Z/?qs=%2Fha2pyFadujg7AoXfk8n23aJzAqS8jh7wcJsfqlMxxXy87FYV7qT7Q%3d%3d>.

INTENTIONALLY LEFT BLANK.

Appendix. Light Pipe Schematic

List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
ARL	US Army Research Laboratory
CAD	computer-assisted design
COTS	commercial off the shelf
GTB	Guidance Technology Branch
LED	light-emitting diode
PCB	printed circuit board
TIR	total internal reflection

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

2 DIRECTOR
(PDF) US ARMY RESEARCH LAB
RDRL CIO LL
IMAL HRA MAIL & RECORDS
MGMT

1 GOVT PRINTG OFC
(PDF) A MALHOTRA

26 DIR USARL
(PDF) RDRL WMF
P PEREGINO
RDRL WML F
B KLINE
B ACKER
B ALLIK
T BROWN
S BUGGS
E BUKOWSKI
J COLLINS
J CONDON
B DAVIS
M DON
D EVERSON
D GRZYBOWSKI
R HALL
J HALLAMEYER
M HAMAQUI
T HARKINS
M ILG
J MALEY
C MILLER
P MULLER
B NELSON
D PETRICK
K PUGH
N SCHOMER
B TOPPER